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Corrosion Resistance of Materials for Renovation of The United States Botanic Garden Conservatory

E. Escalante
R. E. Ricker

U.S. DEPARTMENT OF COMMERCE
Technology Administration
National Institute of Standards
and Technology
Materials Science and Engineering Laboratory
Metallurgy Division
Corrosion Group
Gaithersburg, MD 20899

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Introduction

The United States Botanic Garden was constructed in 1933, using state-of-the-art cantilever aluminum roof trusses for the dome with aluminum and steel structural framing [1]. Over the years, this structure has deteriorated to the point that a major renovation is required, and the primary cause of the deterioration is corrosion of the metals in the lattice frame.

Examination after 60 years of continual use, indicates that the structure has performed well, except in areas that remain wet for extended periods of time. The aluminum alloy used in construction, 17 ST, is prone to exfoliation corrosion under these wet conditions, and this form of corrosion was found extensively throughout the high moisture environment of the Palm House dome. In 1971, the Corrosion Group at the National Institute of Standards and Technology (NIST) provided a study that identified this corrosion attack and recommended an interim repair to the structure [2].

The supporting steel originally specified for use in this structure was ASTM A9-24, used with a coating of an oil-based red lead primer and an overcoat of aluminum graphite paint. The steel was site painted with one coat of aluminum paint. Currently, the paint on the structural steel is cracking and flaking. These cracks expose the underlying steel to air and water which results in corrosion. Corrosion of the lattice frame members is most severe at locations where moisture collects such as the intersection of the horizontal and diagonal lattice members and at the base of the steel columns where they enter the concrete plinth [3].

Problem Statement

The purpose of this report is to evaluate the corrosivity of the greenhouse environments and their effect on materials considered for restoration of the Botanic Garden Conservatory. On the basis of this evaluation, recommendations are made on materials which will provide the best performance in these environments. To accomplish this goal of materials selection, the range of conditions anticipated in the greenhouses, in combination with the various herbicides, pesticides, and fertilizers normally used are considered. Special corrosion control considerations, where necessary, are pointed out.

The information presented here is intended to serve as a general guideline to the architects and engineers responsible for designing the details of the botanic garden conservatory. Within the time limits of this review, the authors can only address the major problems that the designers will encounter and some of the more important details that will lead to a successful design. The objective is to provide an awareness of corrosion pitfalls, and a realization that most corrosion problems can be avoided by applying experience, and common sense knowledge to the new design.

Environmental and Structural Features

Greenhouse Environments

A prominent feature of the botanic garden conservatory is the palm house dome, rising to a height of 27 meters and centrally located in the structure. On the north side of the dome is the Garden Court, housing two pools. On the other three sides of the dome are the low houses made up of the Ornamental Tropical house on the West, the Mediterranean house to the Southwest, the Desert house on the Southeast, and the Dinosaur Garden house on the East side. Each of these greenhouses has its own unique environment, ranging from the relatively dry Desert house, with a simulated rainfall of 25 cm/yr and a relative humidity as low as 15%, to the tropical Palm house dome where moisture simulates a rainfall greater than 250 cm/yr and a relative humidity of 80%.

Moisture is necessary for the health of the gardens in the greenhouses, and by itself, clean water will produce a minimum of corrosion problems. However, when soluble corrosive ions are present with the moisture, the rate of corrosion of the framing and structural materials will increase significantly. An examination of the herbicides, pesticides, and fertilizers used in the conservatory indicates that some of the chemicals used are potentially corrosive. This is not to say that they should not be used, but they should be used with an awareness to their possible damage to surrounding material. Impingement of sprays on conservatory walls must be kept to a minimum. Table 1 is a list of twenty-four chemicals commonly used on the plants at the botanical garden conservatory. Eight of these are chlorinated hydrocarbon biocides, capable of introducing chloride ions recognized as a pitting corrosion accelerator, and one is a fertilizer containing nitrate, phosphate, and ammonium ions, which produce corrosive electrolytes. The eight biocides are:

1). TEMPO 2 EC
2). MAVRIK AQUAFLOW
3). PENTAC WP
4). TALSTAR 10 WP
5). BANROT
6). ORTHO TRIFORINE EC
7). RUBIGAN 50W
8). DACONIL 2788 WDG.

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The fertilizer is PETERS (R).

Other possible sources of corrosive chemicals are window cleaning agents, which are typically highly alkaline solvents that are corrosive to aluminum alloys. These corrosive conditions will develop around entrance doorways and windows that are periodically cleaned. This is not a problem in the greenhouses, since the greenhouse glass walls are not chemically cleaned at any time. However, some glass sections of the greenhouses are whitewashed on the outside to control sunlight. Typically, these are titanium oxide or calcium carbonate based powders applied with a water soluble binder, that are not expected to result in any serious problems to the structural metals. Rainfall tends to remove water soluble components from the whitewash, further reducing any possibility of corrosive salts. More will be said on this subject in the section on performance of materials.

It will be mentioned, as a precaution, that mercury and its salts cause rapid attack of all aluminum alloys, and it is imperative that these chemicals be kept out of the greenhouses [4]. None of the twenty-four chemical salts listed in Table 1 contain mercury. However, mercury's ability to breakdown the aluminum passive surface, amalgamate with the aluminum, which subsequently oxidizes, makes it an especially agressive chemical agent to be avoided.

<u>Materials</u>

Three groups of materials are examined for suitability as structural and framing materials for the Botanic Garden Conservatory. These are five aluminum alloys, four ferrous alloys, and two nonmetallic composites. Table 2 lists the composition and properties of these materials.

a. Aluminum Alloys

The aluminum alloys have excellent resistance to corrosion in the atmosphere and in solutions of neutral and near neutral pH, figure 1. However, their corrosion resistance decreases as the copper content of the alloys increases. Thus, for exposure in an unprotected condition, copper-free alloys are generally preferred for this type of exposure [5][6]. Three decades of atmospheric exposure testing has shown that aluminum alloys, in general, perform better in an uncoated condition, and this is also true for anodized aluminum [7]. There are some benefits from anodized aluminum, but because the the possible localization of corrosion, we are suggesting that it it not be used for this purpose. Therefore, it is recommended that the aluminum structural components not be coated for this botanic garden conservatory application.

The two 2xxx series wrought aluminum alloys are of historical significance, since the 2017-T4 alloy, with the old designation of 17 ST, was used in the original glass framing, and the 2219-T6 aluminum alloy was the material recommended by

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NIST as a replacement during repairs in 1971. The 2219-T6 alloy is chemically similar to 2017, minimizing galvanic interaction with the original material, but because of its different tempering treatment, it is more resistant to localized attack, such as exfoliation. Nevertheless, the presence of the copper as a major alloying element in these alloys, added to improve physical properties, makes this alloy series less desirable in spite of its higher strength, and therefore, the 2xxx series aluminum alloys are not recommended for use in the conservatory environment.

Aluminum alloy 3004-H32 was also used in the original dome structure. This alloy, containing manganese (Mn) and magnesium (Mg) as major alloying elements, is a non-heat treatable alloy used in food processing equipment and architectural products where corrosion resistance is required. To a large extent, this resistance to corrosion is due to the similarity in solution potentials between the precipitates and matrix of the alloy. In some cases, copper is added to improve its properties, as apparently was done with this alloy used on the conservatory [8]. The properties shown in Table 2 are for a 3004 aluminum alloy without additions of copper, hence, its lower tensile properties, compared to the other aluminum alloys. This material, without copper as an alloying element, is suitable for use in the conservatory environment, but its limited availability in extruded structural forms restricts its use.

In 1971, repairs to the dome were made with 6061-T6 [3]. This alloy belongs to commonly available, heat treatable 6xxx series alloys recognized for their versatility of application and corrosion resistance. This particular alloy, 6061-T6, contains a small amount of copper as an alloying addition to improve its physical properties, but its corrosion rate in the atmosphere is superior to the 3004 aluminum alloy previously described (Table 2). These corrosion data are taken from the ASTM atmospheric corrosion test program, which included the 3004 and the 6061 alloys in its exposure matrix [5]. Alloy 6063-T6 is another 6xxx series aluminum alloy considered, which has slightly lower tensile properties than the 6061, but superior corrosion properties resulting from the absence of copper in its composition. Both of these alloys, 6061-T6 and 6063-T6, are readily available in a variety of extruded structural forms. The 6061-T6 alloy will perform well in the conservatory environment, and is recommended for use where higher strength is necessary. The glazing members supporting the glass do not require a high strength material, making alloy 6063-T6 especially well suited for this application, and this alloy is also recommended for use in the conservatory environment.

b. Ferrous Alloys

The ferrous alloys are subdivided into two groups, the carbon steels and the stainless steels. The carbon steel alloys are used to provide structural support for the glasshouses. Three carbons steels are listed in Table 2, the steel used in the original construction of the conservatory, ASTM A 9-24 and two contemporary steels, ASTM A 36 and ASTM A 500. The specification for the A 9 steel was discontinued in 1936, and this steel is no longer available. A 36 steel is very similar to A 9 steel, and is a

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common structural steel used in buildings, bridges, and tanks, to name a few applications. A 500 steel is also similar to the A 9 steel, and is the ASTM designation for structural tubing. There are many carbon steel designations for a wide variety of applications, where the carbon content and the manner in which the steel is formed are varied. These variations have a great effect on the physical properties of steel, but it is important to point out that, in general, the corrosion rate of all these low carbon steels is essentially identical [4]. Furthermore, all carbon steels must be coated to provide protection against corrosion. In addition to coating, tubular steel should be capped and sealed to prevent intrusion of moisture, reducing the possibility of corrosion on the inner wall of the steel.

Often times copper is added to carbon steels to improve their pitting performance, especially at slightly elevated temperatures near the boiling point of water, but at room temperature the improvement is small. Measurements of corrosion rates of unprotected A 36 and A 690, a copper bearing steel, in sea water and in the atmosphere, indicated that the corrosion rates of both were very similar, with the A 690 displaying a slight improvement in performance compared to the A 36. When exposed in a coated condition, their performances were indistinguishable [9]. In the same study, the effectiveness of different types of coatings was examined, and it was found that, of the common coatings available for steel in 1977, a zinc rich epoxy primer with a polyamide cured coal tar epoxy top coat finish provided the best protection. In the case of the greenhouse environments, a top coat is applied primarily to improve the esthetic appearance of the primer coated steel structure rather than to protect the primer. Nevertheless, a top coat is recommended. For the conservatory, structural steels such as A 36 or A 500 with a protective coating system are recommended. However, coatings have changed significantly since our study was conducted in 1977 and the choice of a protective system should be made in consultation with reputable coating suppliers.

The compositions and physical properties for two austenitic stainless steels, type 301 SS and type 304 SS, are shown in Table 2. The strength of these alloys is about twice that of the aluminum alloys, but the density of these alloys is about three times that of the aluminum alloys. These alloys are widely used because of their high ductility and ease of fabrication. However, the 300 series alloys, including the two listed, are susceptible to intergranular corrosion (if sensitized), chloride stress corrosion cracking, pitting, and crevice corrosion.

Stainless steels that contain carbon are susceptible to sensitization. Stainless steels require a chromium concentration above some critical value for the environment to maintain their corrosion resistance. When alloys which contain some carbon are exposed to critical "sensitizing" temperatures, chromium carbides ($Cr_{23}C_6$) precipitate at grain boundaries and grow removing chromium from the surrounding matrix. This results in a chromium depleted region adjacent to the grain boundaries where the chromium concentration is below that required to prevent corrosion. Therefore, sensitized alloys are susceptible to intergranular corrosion. For this form of attack, the

material can loose all of its mechanical strength with no outwardly visible evidence of attack. Sensitization can be avoided during alloy fabrication and heat treatment, but if these alloys are welded, the temperature transient in the weld heat affected zone will result in sensitization over a narrow region adjacent to the weld. Intergranular corrosion in this narrow sensitized region adjacent to welds is sometimes referred to as "knife-line" attack as illustrated in figure 2.

Stainless steels are also susceptible to stress corrosion cracking when exposed to stress and halide ions especially chloride ions. Stress corrosion cracking is a form of crack growth that occurs through the combined action of stress and corrosion at a region of stress concentration. This interaction results in the formation of a crack which then continues to grow through this interaction until the stress in the remaining ligament of the steel exceeds the fracture strength of the steel and catastrophic failure results. Numerous catastrophic failures have occurred in stainless steels because of this form of attack and these failures are almost always due to the presence of chloride ions and, frequently, the concentration of chloride ions in crevices to concentrations above that expected when the alloy was selected for the application is also blamed for the failures.

Stainless steels are also susceptible to pitting and crevice corrosion if the concentration of halide ions exceeds critical concentrations on the surface of the alloys or in a crevice. For a crevice, the concentration of the halide ions in the solutions can be quite small, but through repetitive wetting and drying of the crevice the concentrations can become quite high destroying the protective (passivating) film that forms in these alloys due to the presence of chromium and rapid corrosion in the closed region of the crevice can result, figure 3.

Because stainless steels are susceptible to these forms of corrosion, the solutions to be used in the conservatory contain species that may cause these forms of attack, and the lower strength to weight ratio of stainless steels, these alloys are not recommended for the conservatory environment. Of course, higher alloy stainless steels that are resistant to these forms of attack are available, but these alloys are considerably more expensive that 301 and 304 and are not readily available in product forms suitable for this application.

c. Non-Metallic Materials

In recent times, the non-metallic composites have joined the list of possible structural materials. The two considered here are commonly available, and are used in aircraft, containers, and experimentally in ships. The attractive feature is their high strength to weight ratio, and the fact that they can be shaped in many forms. Major disadvantages are their high cost and the anisotropy of their physical properties as is shown in Table 2. Their tensile properties in the longitudinal direction are 30 to 50 times greater than their tensile properties in the transverse direction. Furthermore, research indicates that the tensile properties of the glass/polymer composite are

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significantly degraded as it absorbs moisture [10-12]. Recent studies indicate that when a graphite/polymer composite is coupled to aluminum, both the metal and the composite are degraded. When coupled, the graphite is cathodic to the aluminum and the metal is severely attacked. At the same time, the pH increases at the graphite causing severe degradation of the polymer. Because of these drawbacks and limitations, these composites are not recommended for use in the conservatory environment.

Performance of Materials

The interaction of materials and the environment can lead to conditions deleterious to the structure, and a thorough understanding of the possible corrosion mechanisms involved, and why they develop, will help to avoid engineering pitfalls that may result in corrosion failures. Corrosion is an electrochemical process where anodic (electron release by metals to form ions) and cathodic reactions (removal of the electrons generated by the ionization of the metals) must occur on the surface of the metals at essentially the same rate. If either reaction is slowed, then both reactions will be slowed. For a smooth homogeneous surface, both reactions must occur at the same locations and this tends to slow the rate of attack. However, corrosion can be accelerated if specific sites can be dedicated to cathodic processes especially if these sites are exposed to large and readily available supply of cathodic reactants such as oxygen rich air. Corrosion can be further accelerated if anodic reactions occur at occluded sites such as a crevice where hydrolysis of the metal ions generated by corrosion results in lowering the pH of the solution in the crevice, figure 3. For this accelerated attack, three things are required: (1) suitable sites for the anodic and cathodic reactions, (2) an electrically conductive path between the anodic and cathodic sites, and (3) a suitable electrolyte which contains dissolved salts (ions) and provides electrical continuity between the anodic sites and the cathodic sites. These three components, the anodes and cathodes, electrical continuity, and an electrolyte, are necessary. Exclude any one of the three, and the rate of corrosion decrease possibly becoming negligible.

When different types of metals are connected by fasteners that conduct electrons between the different metals, they are said to be "galvanically coupled." Because dissimilar metals have different affinities for electrons, galvanic coupling results in one metal acting as a site for cathodic reactions while the other corrodes (acts as the anode). Galvanic interaction between dissimilar metals, is reduced by avoiding or eliminating electrical contact between them or by eliminating the ionic path through the environment. If they must be in electrical contact through mechanical fastening, the area of the cathodic metal exposed to the environment should be kept to a minimum and the anodic metal should never be used for small critical structural elements such as fasteners. For example, stainless steel is cathodic to aluminum and stainless steel fasteners can be used with aluminum, but if aluminum fasteners are used to hold stainless steel the aluminum fasteners corrode rapidly resulting in the system falling apart. When aluminum and stainless steel are used together, the area

of aluminum exposed to the environment should kept greater than ten times the area of stainless steel exposed to the environment [13]. Galvanized steel fastners will provide protection to aluminum as long as the zinc is intact, but once the zinc coating is consumed the steel will cause deterioration of the aluminum structure, and this combination is, therefore, not recommended. Table 3 identifies the various structural component combinations with possible fasteners available, and indicates whether or not the structure/fastener combination is recommended. In this listing, some combinations are identified as acceptable, indicating that a corrosion problem is not expected with this configuration. Those identified as recommended will provide the best corrosion performance and may also have some other property that makes them desirable. For examble, an aluminum fastener will work well with aluminum structural components, but the higher strength of a stainless steel fastener is desirable. A second example is the recommendation of a carbon steel fastener, rather than a stainless steel fastener, for the steel structural components. Carbon steel fasteners are chosen because they are less expensive than stainless steel fasteners and will function just as well, when coated. Welding of like metals is almost always an acceptable method of joining components, and is often chosen over mechanical fastening because of esthetics or ease of manufacture.

Coatings are frequently used to break the electrical circuit between the metals through the environment and prevent galvanic attack, but if coatings are to be used, the cathodic metal (the one that is not attacked by corrosion) should be coated because if only the anodic metal were coated the current generated by the large area of cathodic reactions would be concentrated at any flaw in the coating on the anodic metal. Therefore, where aluminum is joined to steel, it is recommended that the surface of the steel between the joint be coated. The coating applied between the joint can be the same coating system chosen for the rest of the steel structure. If a zinc rich coating is used to protect the steel, the zinc will also provide local protection to the aluminum [4]. It is recommended that the aluminum remain bare, reducing localization of any galvanic attack that may occur. Stainless steel fasteners should be used at the aluminum-steel joints. Furthermore, when joining any dissimilar metals it is especially important that the region of the joint be designed to avoid the collection of moisture and debris.

Some chemicals, in particular those containing halogen ions, such as chlorides and fluorides or other salts containing nitrates and phosphates, are especially aggressive. Most, or perhaps all of the chemicals listed in Table 1, may be necessary for maintenance of the plants in the conservatory. Where possible, it is desirable to avoid chemicals that are chlorinated or are highly acid or highly alkaline. Where these chemicals must be used, then some caution should be exercised to avoid spraying the conservatory walls unnecessarily.

The daily misting and fogging systems that water the plants will rinse away corrosive salts from the internal structural walls of the conservatory. In this way, even where moist conditions cannot be avoided by the nature of the plant environment,

corrosion of the structural walls can be minimized. However, where this rinsing action does not occur, then soluble salts will concentrate resulting in possible corrosive conditions. Thus, a possible corrosion preventive action is a periodic rinsing of the walls of the conservatory, with the intention of rinsing away these accumulated salts. This washing of the walls could be performed annually, and would be directed especially at those areas where water and debris collects on the structural framing.

This rinsing action will not provide the same benefit to the structural steel where it enters the concrete foundation. In this region, the steel columns are exposed to a distinctive environment that is deleterious to the steel. This is discussed in the section on Steel In Concrete.

Structural Design Considerations

An important aspect of corrosion control is the design of structural components configured to avoid the collection of moisture, salts and debris. Good engineering practice involves fabrication of structural members that allow runoff of water. It is essential to avoid orientation of components that result in grooves, channels or corners where moisture and salts can collect. Similarly, welds must be made and placed in such a manner that pooling of moisture is avoided. In some cases, it may be necessary to grind the welds to maintain a smooth profile and avoid accumulation of residues. Crevices are a common source of moisture retention problems and must be minimized. Resting pipes, electrical wiring, etc. on metal components forms crevices where debris and moisture will accumulate with deleterious effects to the structure. Pipes and other utilities can be supported by brackets, reducing the effects of crevices. Thus, an important step in controlling corrosion is the design of details for the structure where corrosive moist debris will not collect.

Compatibility of materials, from the standpoint of corrosion performance, is important in the choice of accessories attached to the structural members of the conservatory. Brackets, hangers, plumbing, gutters, conduit, and monitoring meters are all an important part of the building, but some consideration must be given to possible delitirious effects of attaching these components to the structure.

For example, connecting copper or copper alloy components to the aluminum structure is destructive to the aluminum. Copper ions are so effective in attacking aluminum that even low concentrations of copper in water run-off from a copper accessory, which is not necessarily connected to the aluminum, is sufficient to cause corrosion and pitting of the aluminum. Thus, copper plumbing, copper alloy encased meters, copper gutters, and other copper accessories should not be placed in contact with aluminum, and should not be placed in where water run-off from such accessories will come in contact with aluminum. Where copper must be used, it should be coated to reduce contamination of the aluminum.

Stainless steel or aluminum bracket assemblies that support accessories, can be safely attached to aluminum structures. It is also permissable to use galvanized steel attachments as long as the galvanized coating remains intact and the galvanized assembly can be inspected and replaced when necessary.

Similar compatibility problems are not as acute with the steel structure. Aluminum, steel, galvanized steel, and stainless steel fixtures can be used with the steel structure without any serious effect to the steel.

Steel in Concrete

In general, steel is protected by the highly alkaline environment of the concrete, but the portion of the steel where it exits the concrete and immediately outside of the concrete is susceptible to localized attack, figure 4. This corrosive condition is the result of the different environments that the steel column is exposed to, where the steel in the concrete is cathodic to the steel at the interface and immediately outside of the concrete. The difference in oxygen concentration at the metal/concrete interface plays a major role in this corrosion reaction. To avoid this effect, it is recommended that the steel be coated in this region, especially the portion that extends into the concrete. A zinc rich epoxy primer with a top coat would provide protection, provided it is maintained where it exits the concrete.

Steel entirely encased in concrete is normally passive, and its corrosion is negligible. This is true as long as halide contamination of the concrete is avoided. In the presence of chloride, the passive film on steel, that provides corrosion protection, is destroyed and corrosion of the steel occurs. This corrosion product forms an oxide whose volume is greater than the volume of the steel, resulting in stresses on the concrete that cause it to crack and spall. These cracks provide direct access of the corrosive media to the steel, accelerating the corrosion process. Thus, it is important to avoid chloride contamination of the concrete. The three major sources of chloride contamination are: 1) chloride added during construction, 2) chloride from sprays, and deicing salts tracked in by visitors in the winter.

During winter construction it has been common practice to add chloride bearing salts to concrete to accelerate hydration and reduce its setting time. From the standpoint of corrosion protection, this is extremely bad practice, and additions of any halide salts to concrete must be strictly avoided. The second source of chloride, from sprays, is more difficult to control. Since it is expected that chloride containing sprays will be used, it is necessary to provide the concrete with some barrier to the ingress of these salts, and one of the best forms of protection is a protective coating on the concrete. All surface areas of the concrete that may come in contact with chloride bearing salts should be coated. This coating is important in the spray area and below the ground line, where these salts will collect. The third source of chloride, tracking in of salts, affects the interior floors and walkways, especially those near the entrance to the conservatory. Tracking in of salts on the soles of shoes can be minimized by

placing open weave rubber mats or fibrous rugs at the entrance to clean shoes as visitors enter the building. Coating interior concrete walkways with sealers and minimizing use of deicing salts will also reduce the problem.

Two common and effective coatings for concrete are: a) an epoxy polyamide coating system which is very effective on concrete in indoor environments, or b) a chlorinated rubber coating system as used in swimming pool installations. Either would provide an effective barrier to the diffusion of chloride into the concrete. As stated earlier, the final choice of coating should be made by consulting reputable coating suppliers.

Aluminum In Concrete

Aluminum is an amphoteric metal, and is subject to corrosion attack in environments with a low pH (<4) or high pH (>9), figure 1. Thus, it is important to avoid having aluminum and its alloys in contact with concrete or mortar, since the pH of these environments is very alkaline (>12). Not only would the aluminum degrade, but it would cause spalling and cracking of the concrete.

Maintenance

Proper maintenance is essential to assuring that the expected longevity and safety of the greenhouse structures is achieved. This maintenance program should include a regular detailed inspection of the structure every two years by a knowledgeable, trained individual that will recognize a corrosion problem at its initial stages. In addition, this individual must have the responsibility of checking for obvious signs of coating distress on the steel or other precursors to corrosion problems in other materials. Where coating failures are observed, repairs and coating renovation must be performed promptly. On an annual basis, the inside walls and structural members of the greenhouses should be completely rinsed to remove accumulation of salts, and it may be necessary to mechanically remove tenacious debris by brushing.

Thus, corrosion control involves the proper choice of building materials, good engineering practice, coating protection where necessary, and regular inspection and maintenance. These precautions will assure that the conservatory will reach and, most likely, exceed the 60 year lifetime of the original structure.

In The Absence of Protection and Maintenance

With an improper choice of materials, poor structural design practices, and a lack of corrosion protection measures, the botanic garden structure will succumb to the ravages of moisture and corrosive chemical sprays existing in the botanic garden environment, greatly reducing its expected life. Using conservative figures, an estimate of expected lifetime without protection has been calculated. Without protection to the steel columns in the presence of sprays and moisture, failure of the

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structure could occur in 28 years. This is based on the assumption of a corrosion rate of 0.0016 inches/yr on a 0.5 inch steel section (as found on the Palm House structural steel base), and assumes that the maximum allowable loss is 20% of the steel wall [4]. Where the steel encounters the concrete/air interface, the effects are even more severe and the above lifetime estimate would be further reduced.

Studies on the corrosion rate of several aluminum alloys exposed to the atmosphere in a sheltered and unsheltered condition, indicate that after four years of exposure the corrosion attack of the sheltered specimens is more than twice that of the unsheltered specimens [14]. This accelerated corrosion is attributed the the accumulation of salts and debris on the sheltered specimens. The unsheltered specimens were periodically washed by rain. This points out the importance of rinsing the aluminum structure, especially where salts can accumulate. It also suggests that the lifetime of the new aluminum structure will be significantly lengthened by this rinsing action, in comparison to the original construction which was not washed .

Conclusions

The corrosion performance of the original greenhouse structure is an excellent guide to the performance of the renovated structure. The aluminum alloys produced today are of better quality than those of the 1930's, and this improvement is the result of reduced impurities and inclusions in the melt. Reduction in these contaminants has resulted in an improvement in the corrosion performance of todays aluminum alloys compared to the same alloy of sixty years ago. Therefore, the combination of cleaner aluminum alloys coupled with low copper (6061-T6) or copper-free (6063-T6) aluminum alloys provides confidence that the new botanic structure will exceed the longevity of the original structure.

The A36 and A500 structural steels are very similar to the steel used in the original construction of the botanic garden structure, and their corrosion rates can be expected to be about the same for all cases. Improvement in performance will come about through better coating technology, proper coating procedures and control of the concrete environment. By avoiding chloride additions to the concrete and by providing regular maintenance of the protective coating on the steel, its expected lifetime will be improved, in comparison to the original structure.

Summary

- Two aluminum alloys are recommended for use in the greenhouse environments: 6061-T6 where higher strength is needed, and 6063-T6 where lower strength is acceptable.

- Where steel is used, ASTM A 36 steel or ASTM A 500 with a zinc rich epoxy primer and an overcoat is recommended for use in the greenhouse environments.

- Where steel tube or pipe is used, it is recommended that it be sealed to avoid intrusion of moisture to the interior wall.

- Avoid additions of chloride containing salts to the mortar or concrete in contact with metals during construction.

- Provide a protective coating to the concrete to reduce introduction of salts into the concrete, where it will degrade steel.

- Provide a protective coating to all surfaces of steel where it comes in contact with mortar or concrete.

- Design the structure to avoid pockets that collect moisture, salts and debris, and provide adequate drainage to all surfaces.

- A maintenance program is essential to assure the safety and longevity of the greenhouse structures.

References

1. Thornton, C.H., U. Hungspruke, and R.P. DeScenza, "Vertical Expansion of Vintage Buildings", Modern Steel Construction, (June): p. 35-37, 1991.

2. Ugiansky, G. and J. Kruger, "Failure of Palm House Structural Interior Framing", NBS Report 10 549, National Bureau of Standards, April 1971.

3. Daniel, et al., "Restoration of the United States Botanic Garden Conservatory", Daniel, Mann, Johnson, Mendenhall, February 22 1990.

4. Uhlig, H.H. and R.W. Revie, "Corrosion and Corrosion Control", Third Edition ed. New York: John Wiley & Sons. 1984.

5. ASM, "Corrosion", Metals Handbook Ninth Edition, Vol. 13., Metals Park, OH: ASM International. 1987.

6. Boyd, W.K. and F.W. Fink, "Corrosion of Metals in the Atmosphere", MCIC-74-23, Battelle's Columbus Laboratories, August 1974.

7. Sowinski, G. and D.O. Sprowls, "Weathering of Aluminum Alloys" in Atmospheric Corrosion, W.H. Ailor, ed., John Wiley and Sons: New York. p. 297-328, 1982.

8. anon, "Federal Conservatory Uses Aluminum-Alloy Framing", Engineering News Record, (April 14): p. 539-542, 1932.

9.   Escalante, E., et al., "Corrosion and Protection of Steel Piles in a Natural Seawater Environment", NBS Monograph 158, NIST, June 1977.

10.   Ricker, R.E., E. Escalante, and M.R. Stoudt. "Environmental Effects on Polymer Matrix Composites" in Tri-Services Conference on Corrosion. Plymouth, MA: The Army Materials Technology Laboratory, Watertown, MA, 1992.

11.   Stoudt, M.R., E. Escalante, and R.E. Ricker. "The Influence of Water on the Mechanical Properties of a Glass-Epoxy Matrix Composite" in ADVMAT. San Diego, CA: 1991.

12.   Stoudt, M.R., E. Escalante, and R.E. Ricker, "The Influence of Water on the Mechanical Properties of a Glass-Epoxy Matrix Composite", Ceramic Trans., 19: p. 993-1000, 1991.

13.   Godard, H.P., et al., "The Corrosion of Light Metals", New York: John Wiley & Sons, Inc. 1967.

14.   Feliu, S. and M. Morcillo, "Atmospheric Corrosion Testing in Spain" in Atmospheric Corrosion, W.H. Ailor, ed., John Wiley and Sons: New York. p. 913-921, 1982.

Table 1
Chemicals Used In the U.S. Botanic Garden Conservatory

Product	Uses Chemical Family	Chemical Name	Manufacturer
TEMPO 2 EC	pyrethroid insecticide	Cyano(4-Fluoro-3-phenoxyphenyl)methyl 3-(2,2-dichloroethenyl)-2, 2-dimethyl-cyclopropanecarboxylate	Mobay Corp Kansas City, MO
MALATHION EC 5	Insecticide	0,0-dimethyl phosphorodithioate of diethyl mercaptosuccinate	Miller Chemical & Fertilizer Corp Hanover, PA
ISOTOX	Insecticide	not provided	Chevron
SUNSPRAY 6E PLUS	spray oil ?	alkyl aryl polyoxyethoxy ethanol nonionic surfacant, and alkylphenol coupler	Sun Refining and Marketing Co Philadelphia, PA
ENSTAR 5E	sesquiterpenoid ester	Kinoprene, C18H28O22	Zoecon Corp Palo Alto, CA
Oxamyl Concentrate 42	Insecticide Nematicide	methyl N'N'-dimethyl-N-(methylcarbamoyl)-oxy-1-thiooxamimidate	E.I. du Pont de Nemours & Co Wilmington, DE
KNOX OUT 2FM	Insecticide	0,0-diethyl 0-[6-methyl-2-(1-methylethyl)-4-pyrimidinyl] phosphorothioate	Pennwalt Corp Philadelphia, PA
SLUGIT LIQUID	nematicide ?	metaldehyde	Murphy Chemical Ltd England
MAVRIK AQUAFLOW	Insecticide fluorinated pyrethroid	[(RS)-2-[2-chloro-4-(trifluoromethyl)anilino]-3-methylbutanoate]	Sandoz Crop Protection Corp Des Plaines, IL
PENTAC WP	miticide cyclic organochlorine	decachloro bis(2,4-cyclopentadiene-1-yl)	Sandoz Crop Protection Corp Des Plaines, IL

Table 1 (continued)
Chemicals Used In the U.S. Botanic Garden Conservatory

Product	Uses Chemical Family	Chemical Name	Manufacturer
SURFLAN A.S.	herbicide	3,5-dinitro-n4-dipropylsulfanilamide	Dow Elanco Indianapolis, IN
ROUNDUP	herbicide	isopropylamine salt of glyphosate	Monsanto Co St. Louis, MO
AVID 0.15 emulsifieable concentrate	Insecticide miticide	Avermectin B and Hexanol	Merck & Co. Inc. Rahway, NJ
PETERS (R)	fertilizer 20-20-20	potassium nitrate monoammonium phosphate urea	
TALSTAR 10 WP	insecticide miticide pyrethroid pesticide	3-(2-chloro-3,3,3-trifluoro-1-propenyl)-2,2-dimethyl-(2-methyl-[1,1'-biphenyl]-3-yl) methyl ester and Cyclopropanecarboxylic acid	FMC Corp Philadelphia, PA
MARGOSAN-O	not provided	azadirachtin	Grace/Sierra Crop Protection Co. Milpitas, CA
SUBDUE 2E	acetanilide fungicide	N-(2,6-dimethylphenyl)-N(methoxyacetyl)-alanine methyl ester	CIBA-GEIGY Corp Greensboro, NC
BANROT	40% wettable powder	5-ethoxy-3-trichloro-methyl-1,2,4-thiadiazole and dimethyl 4,4'-O-phenylenebis (3-thioallophanate)	Sierra Crop Protection Co Milpitas, CA
ORTHO TRIFORINE EC	pesticide	N,N'-(1,4-piperazinediyl-bis-(2,2,2-trichloroethylidene))-bis-(formamide)	Chevron Environmental Health Center, Inc Richmond, CA

Table 1 (continued)
Chemicals Used In the U.S. Botanic Garden Conservatory

Product	Uses Chemical Family	Chemical Name	Manufacturer
RUBIGAN 50W	fungicide	alpha-(2-chlorophenyl)-alpha-(4-chlorophenyl)-5-pyrimidine-methanol	Elanco Products Co Indianapolis, IN
DACONIL 2787 WDG	not provided	tetrachloroisophthalonitrile and chlorothalonil	Fermenta ASC Corp Mentor, OH
TREFLAN E.C.	herbicide	alpha,alpha,alpha-trifluoro-2,6-dinitro-N,N-dipropyl-p-toluidine	Elanco Products Co Indianapolis, IN
ORTHENE 75 S	insecticide organic phosphorus	P.S-dimethyl acetylphosphoramidothioate	Chevron Environmental Health Center, Inc Richmond, CA
BENLATE	Benzimidazole	methyl 1-(butylcarbamyl)-2-benzimidazolecarbamate	E.I. du Pont de Nemours & Co Wilmington, DE

Aluminum Alloys

Material [1]	Si	Cu	Mn	Mg	Tensile Strength MPa (ksi)	Yield Strength 0.2% offset MPa (ksi)	Elongation %	Brinell Hardness
2017-T4 Al 17 ST (old designation)	-	4	0.5	0.5	427 (62)	276 (40)	22	105
2219-T6 Al	-	6.3	0.3	-	414 (60)	290 (42)	10	-
3004-H32 4 S 1/8H Al (old designation)	-	-	1.2	1	214 (31)	172 (25)	17	52
6061-T6	0.6	0.27	-	1	310 (45)	276 (40)	17	95
6063-T6	0.4	-	-	0.7	241 (35)	214 (31)	18	73

[1] Aluminum Standards & Data, The Aluminum Assoc., 1973

Ferrous Alloys

Material	C (max)	P	Cr	Ni	Tensile Strength MPa (ksi)	Yield Strength 0.2% offset MPa (ksi)	Elongation %	Rockwell Hardness
ASTM A9-24 Steel [4]	0.27	0.1	0.27	-	414 (66)	228 (33)	22	-
ASTM A36/A 36M-91 [3]	0.26	0.04	-	-	475 (70)	235 (34)	23	-
A 500 - 90a [3]	0.26	0.04	-	-	400 (58)	290 (42)	23	
Type 301 SS (annealed) [2]	0.15	-	17	7	760 (110)	276 (40)	60	B 85
Type 304 SS [3]	0.08	-	18	8	552 (80)	221 (32)	45	B 95

[2] The Making Shaping and Treating of Steel, 7th Edition, USS, 1957
[3] Metals Handbook, 9th Edition, ASM,1978
[4] C.H. Thornton, U. Hungspruke, R.P. DeScenza, "Vertical Expansion of Vintage Buildings", Modern Steel Construction, June 1991.

Table 2 (continued)
Structural Materials Considered For The U.S. Botanic Garden Conservatory

Non-Metallics		
Material	T.S. Transverse MPa (ksi)	T.S. Longitudinal MPa (ksi)
Graphite/Polymer Composite [4]	28 (4)	1450 (210)
E Glass/Polymer Composite [5]	28 (4)	780 (113)

[4] Composites For Extreme Environments, N.R. Adsit, ASTM STP 768, 1982
[5] Composite Materials, K.K. Chawla, Springer-Verlag, 1987

Table 3
Acceptability of Fastener/Structure Combination
To Minimize Corrosion Problems

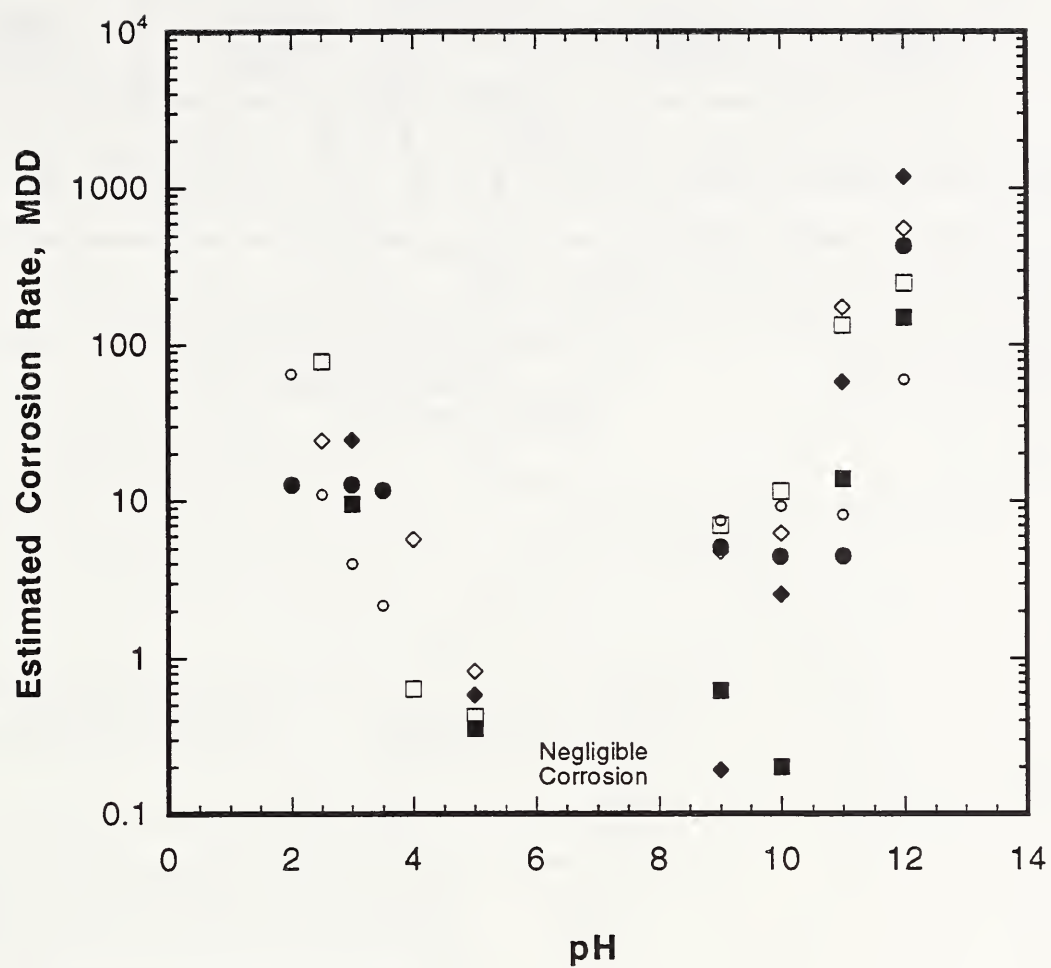| Fastener	Structure		
	Aluminum-Aluminum	Steel-Steel	Aluminum-Steel
Aluminum	acceptable	not recommended	not recommended
Galvanized Steel	not recommended	acceptable	not recommended
Steel	not recommended	recommended	not recommended
Stainless Steel	recommended	acceptable	recommended
Weld	acceptable	acceptable	not recommended

Figure 1

The influence of pH on the corrosion rate of
aluminum alloy 1100 (essentially pure Al).

Parent or Base Metal | Weld Heat Affected Zone | Fusion Zone | Weld Heat Affected Zone | Parent or Base Metal

Stainless Steel

Narrow Regions of Critical
Thermal History During
Welding Process

Cr Carbide precipitates nucleate
and grow at grain boundaries

The growth of chromium carbide precipitates
removes chromium from the adjacent grains
resulting in a chromium concentration below
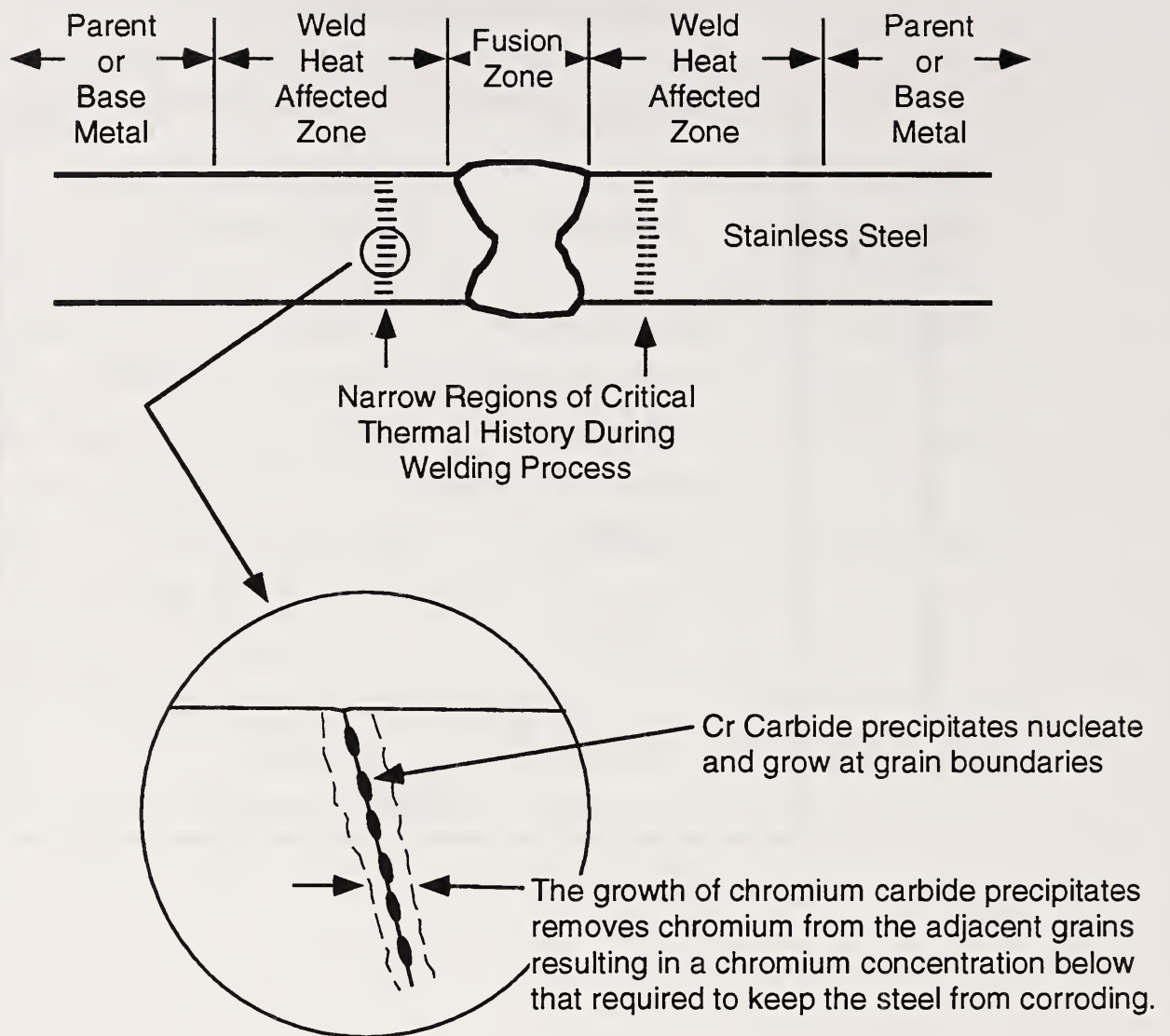that required to keep the steel from corroding.

Figure 2

Schematic of the "knife-line" attack that can occur adjacent to
welds in stainless steel alloys that contain sufficient quantities of
carbon to become "sensitized" during heat treatments such as
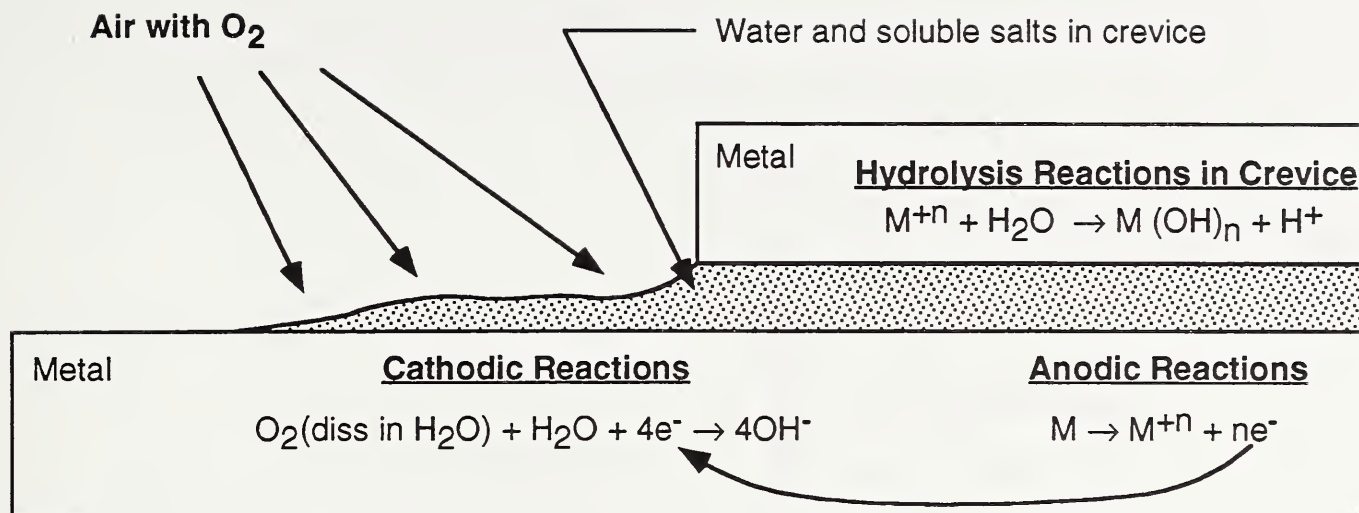occur in the heat affected zone during welding.

Air with O$_2$

Water and soluble salts in crevice

Metal

Hydrolysis Reactions in Crevice

$M^{+n} + H_2O \rightarrow M(OH)_n + H^+$

Metal

Cathodic Reactions

$O_2(\text{diss in } H_2O) + H_2O + 4e^- \rightarrow 4OH^-$

Anodic Reactions

$M \rightarrow M^{+n} + ne^-$

Figure 3

An Illustration of the Importance of Crevices in Accelerating Corrosion

Air with O$_2$
Water Standing at Col. Base.

Steel

Cathodic Reactions

O_2(diss in H_2O) + H_2O + 4e$^-$ → 4OH$^-$

Concrete

Anodic Reactions

Fe → Fe^{+2} + 2e$^-$

Fe^{+2} → Fe^{+3} + e$^-$

Precipitation of
corrosion products
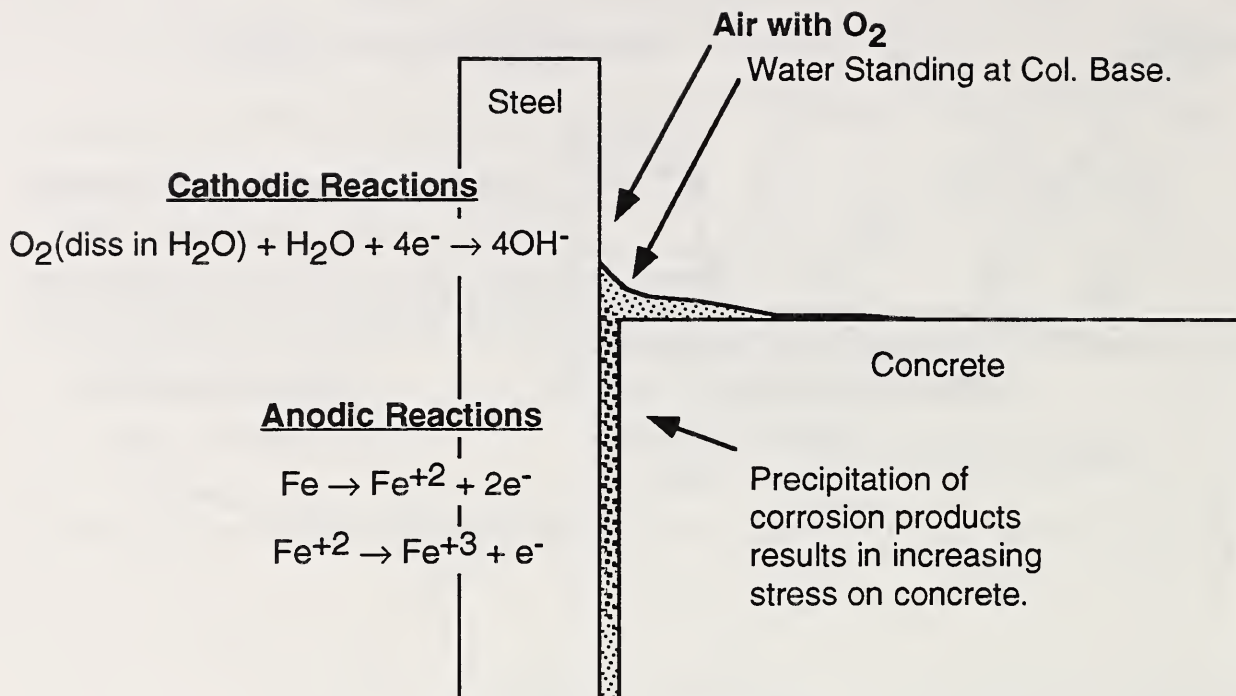results in increasing
stress on concrete.

Figure 4

An Illustration of corrosion processes that occur when steel
encased in concrete is exposed to standing water.